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Multi-hull Flow Visualization: An investigation of flow visualization techniques for trimaran hulls

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14. ABSTRACT
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Flow visualization, Trimaran, Particle Image Velocimetry, Wake between hulls, pressure on hull

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Abstract

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After an analysis of the effectiveness and comparative cost of several methods, it was concluded that the best technique for visualizing the flow on the surface of the hulls is boiled linseed oil mixed with artist's paint. Particle Image Velocimetry is the recommended method for visualizing flow around the hulls. For assessing the pressures on the hulls and the wakes between the hulls, shear and pressure sensitive films from Innovative Scientific Solutions, Inc. appeared the most promising, although more development is still required.

Acknowledgements

This report is the culmination of work conducted by students working in the National Research Enterprise Intern Program sponsored by the Office of Naval Research. This program provides an opportunity for students to participate in research at a Department of Navy laboratory for 10 weeks during the summer. The goals of the program are to encourage participating students to pursue science and engineering careers, to further education via mentoring by laboratory personnel and their participation in research, and to make them aware of Navy research and technology efforts, which can lead to future employment.

At the Naval Surface Warfare Center Carderock Division, the single largest employer of summer interns is the Center for Innovation in Ship Design (CISD), which is part of the Ship Systems Integration and Design Department. The intern program is just one way in which CISD fulfils its role of conducting student outreach and developing ship designers.

The student team consisted of:

Tom Denz

Rajeev Shrestha

Stephanie Smith

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Introduction

The objective of this study was to investigate innovative methods of visualizing water flow characteristics, specifically for a trimaran hull configuration moving at constant speed in calm water. This innovation cell was chosen to provide a fresh outlook, a non-naval engineering perspective, on this hydrodynamic problem.

The major requirement was that these techniques would make it possible to verify the fluid dynamics phenomena predicted by Computational Fluid Dynamics (CFD) software packages. These techniques would provide enhanced insight into the design of integrated hulls and propulsors by helping naval architects better understand flow characteristics of multihulls. The methods selected had to be compatible with the David W. Taylor Model Basin at the Naval Surface Warfare Center Carderock Division (NSWCCD). Cost and safety of test personnel and equipment were also major concerns.

Background

Figure 1: The Maxi Trimaran Groupama 3

A trimaran is a boat with three hulls generally consisting of one main hull and two smaller outer hulls. It has potential use for the U.S. Navy as a high-speed sealift vessel or combatant due to its smaller drag, larger deck area, and greater stability than monohulls.

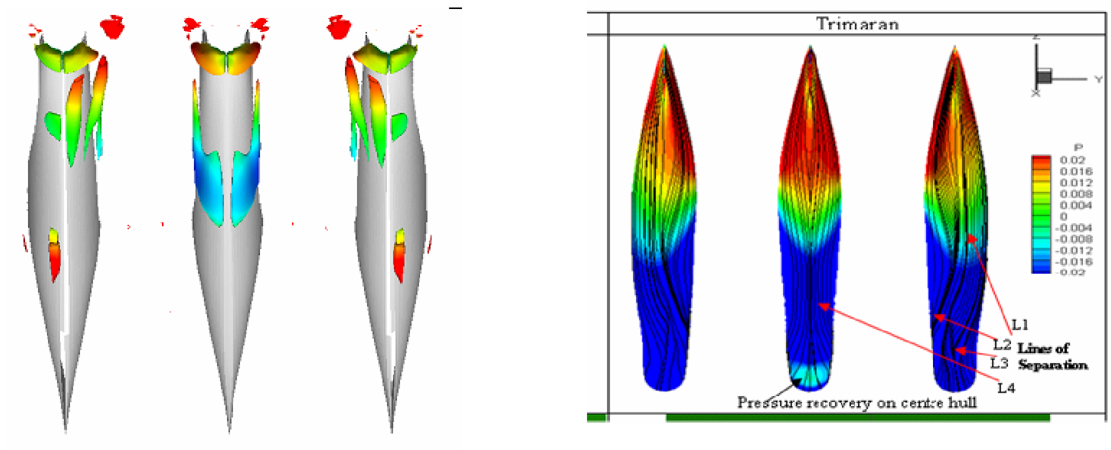


Figure 2: A sample of Computational Fluid Dynamics (CFD) computer output

Since trimarans have been proven valuable to the U.S. Navy, it is important to develop a greater understanding of the flow around such hull configurations. Not much information is known yet of the flow around trimaran hulls; however, CFD can be helpful in that analysis. CFD tools use numerical methods and algorithms to solve and analyze problems that involve fluid flows.

In order to validate the legitimacy of the CFD output, experimental techniques are needed to compare the simulated results with physical data. In this study, several different flow visualization techniques have been surveyed that could verify the numerical predictions. These methods have been divided into four areas of interest: flow on the hulls, pressures on the hulls, wakes between the hulls, and flow around the hulls. The specific techniques have been assessed based on effectiveness, efficiency, and cost.

Flow On The Hulls

The first area of interest is flow on the hulls. It is essential to explore, examine, and understand fluid behavior on the hull when designing any boat or ship. This is particularly important for multihulls for which less is known. In order to qualitatively characterize this flow, several techniques can be employed. Each of these techniques involves the application of a foreign substance onto the ship hull.

Tufts

The tufts method involves attaching pieces of string or yarn of varying length to the hull at certain points on a grid. As the model is run through the tank, real-time pictures are taken to see how the tufts move with the flow. This method has been commonly used in hydrodynamic and aerodynamic studies.

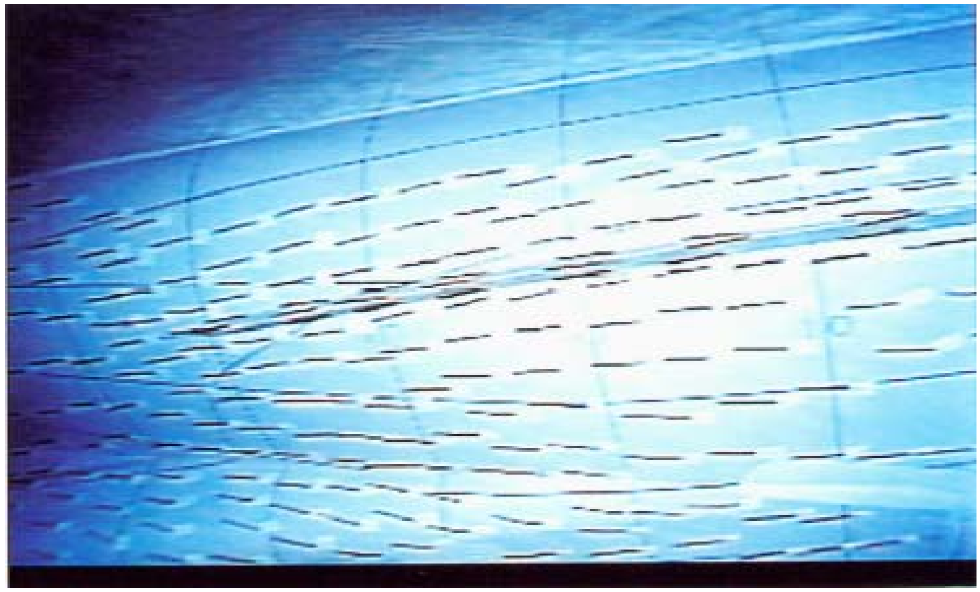


Figure 3: Underwater flow visualization-verification of bilge keel alignment using tufts.

Tufts are beneficial to use because they provide a visual representation of the flow streamlines. The material used, mainly string or yarn, is extremely cheap. The entire procedure can be done without expensive or sophisticated equipment. Moreover, the tufts do not pollute the water; therefore, the addition of a foreign substance is not an issue.

There are some disadvantages. While tufts are low in cost and the procedure is straightforward, the number of trials along with the tow-tank lease time increases the cost of this method. Furthermore, tufts are tedious to attach to the hull section, and the integrity of the data is questionable because the tufts might not always perfectly follow the flow. On smaller models, the tufts themselves might interfere with the flow characteristics. In addition, one or more cameras must be positioned to take pictures as the test is being conducted. The need for real-time pictures involves extra effort.

Oil Droplets

In this particular technique, drops of heavy oil are applied onto the hull. The oil droplets streak in a pattern to follow the water flow on the hull, giving qualitative flow characteristics. The end result provides insight into the fluid dynamics on the hull by visually representing flowlines, flow speeds, and flow separation.

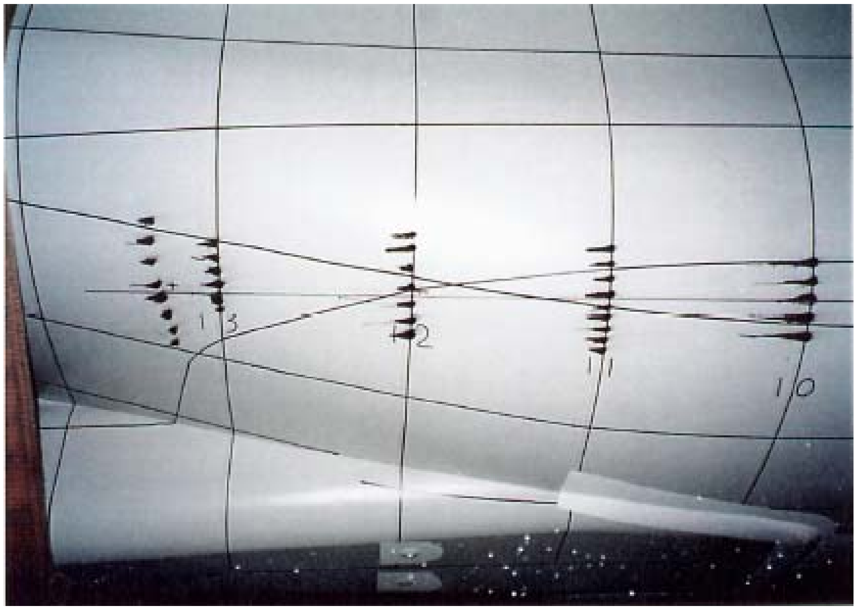


Figure 4: Oil-dot streaking in way of the starboard slide bilge keel on Model 5522, representing the NOAA FRV-40

The chief advantage of this technique is that heavy oil is cheap and readily available. Additionally, the method is considered relatively simple and has already been used at NSWCCD. However, when applying heavy oil to the hull section, a foreign substance is introduced. Introducing a foreign substance in this manner might pollute the water, and at times, interfere with the flow. Moreover, oil droplets are extremely tedious to apply and provide only qualitative readings of the flow. Oil droplets, even with thick and heavy oil, also tend to run after they are applied to the hull and before testing due to the influence of gravity. Another thing to consider is that while oil is cheap, the procedure to go along with the material is expensive since it requires several trials and therefore additional tow-tank time. Multiple applications of oil droplets are needed to acquire sufficient test data on the flow characteristics.

Artists' Paint and Linseed Oil Mixture

This method is similar to the oil droplet method. The main differences are that linseed oil mixed with artists' paint is used instead of heavy oil. The paint to oil ratio should be optimized based on the speed of the test performed. The procedure involves wiping the hull with a layer of linseed oil first as a preparation and then applying the artists' paint and linseed oil mixture at strategic locations. The mixture should be patted on the hull section in a thick fashion with high points showing ("stucco fashion") rather than painted on in a smooth coat. Much like the oil droplets method, the paint mixture streaks in a pattern and follows the flow of water on the hull, giving a qualitative description of the flow.

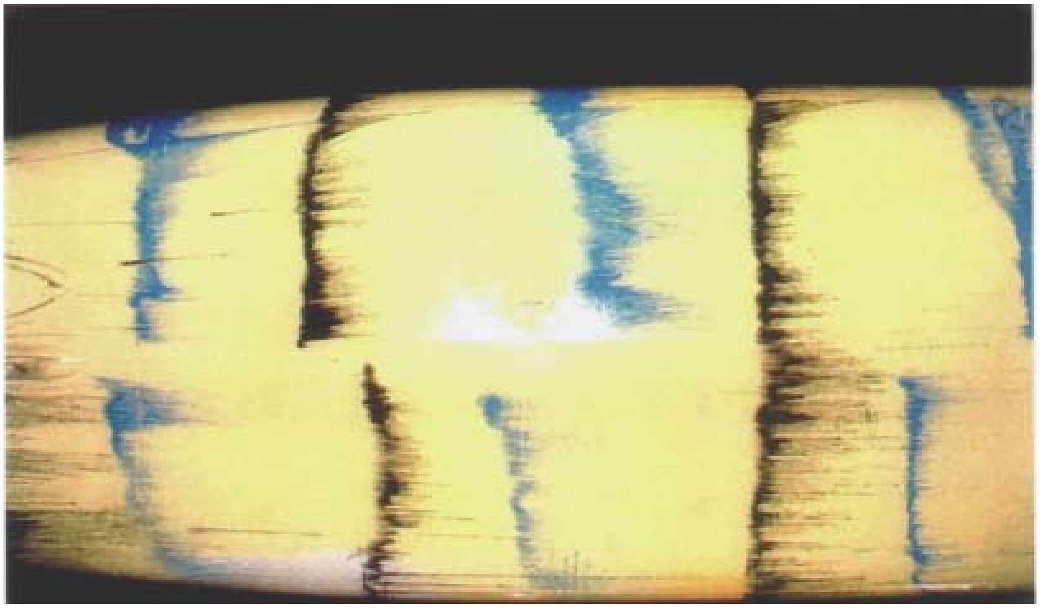


Figure 5: Photograph of hull bottom flow visualization results using artists' paint and linseed oil for Model 9080, representing the T-AGS 60

Like the heavy oil, both artists' paint and linseed oil are common, inexpensive substances. The paint and oil mixture, however, runs less than the heavy oil method. Other benefits are that the technique provides a convenient, visible representation of water flow and has been done in-house. It represents a more recent procedural innovation at NSWCCD.

There are some drawbacks. The application of the paint and oil mixture on the hull can be cumbersome. A learning curve is required to achieve the proper paint to oil mixture ratio for different test speeds. Like the oil droplets, the paint and oil mixture also introduces foreign substances, which might pollute the water and potentially affect the flow. When the test is completed, a very slow reverse speed is required of the carriage in order to preserve the streaking results. Moreover, while the materials are inexpensive, the tow-tank time involved with the procedure can be expensive.

Skin Friction Sensor

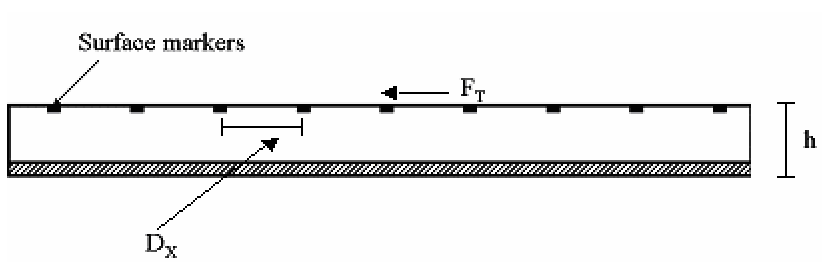


Figure 6: Diagram of how the skin friction sensor works with the tangential force F_T, thickness h, and displacement D_x

The skin friction sensor, a film currently being developed by a company called Innovative Scientific Solutions, Inc. (ISSI) in conjunction with Penn State University, is a

flexible coating with embedded particulates that can be applied to the hull. The sensor is composed of an elastic polymer with a known thickness and shear modulus that can be modified for different sensitivities (ISSI report). When a tangential load is applied to the film, it deforms elastically but without compressing or yielding (see Figure 6). The embedded surface markers contained in the film displace as the film experiences shear, giving a visual output of the flow along the hull. The displacement is a function of the applied force, the thickness of the film, and the shear modulus of the film. The displacement can be measured using cross-correlation from images of the surface at the flow on and flow off conditions. A sample of the result is shown in Figure 7.

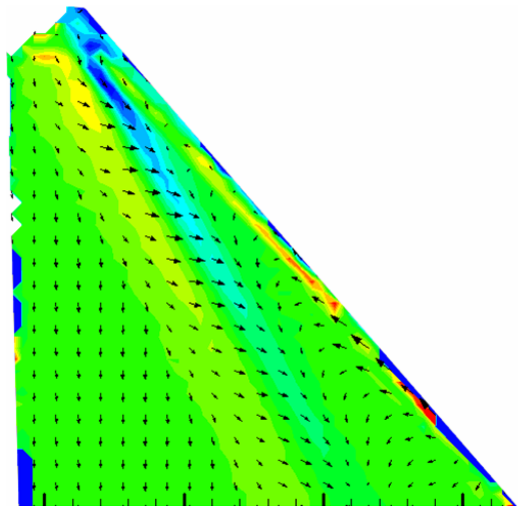


Figure 7: Sample of skin friction sensor output

ISSI reports that the skin friction sensor provides a better quality output than most other flow visualization methods. Furthermore, the method does not introduce a foreign substance that pollutes the water. However, since this technique is still in development, the integrity of the results has not yet been assessed. The only reported results have been through ISSI, the company developing the technique; therefore, the actual quality of the results is unknown to the public. The cost is also not yet available.

Pressure on the Hull

Knowing the pressure distribution on the hull is another vital component of designing hulls. It is essential to understand the forces that are being applied to a hull in order to determine how strong the hull material needs to be. The interactions in multi-hull configurations are more complex and would benefit from additional study. Having physical measurements to verify CFD predictions of pressures could greatly improve hull designs. The following visualization methods could prove useful in achieving that goal.

Pressure Taps

The first method for determining pressures on the hull is the pressure tap method. Pressure taps are pressure sensors individually mounted from within the hulls in a grid pattern. As a test is being run, the pressure taps measure the pressure applied at a discrete point and record the data to a computer.

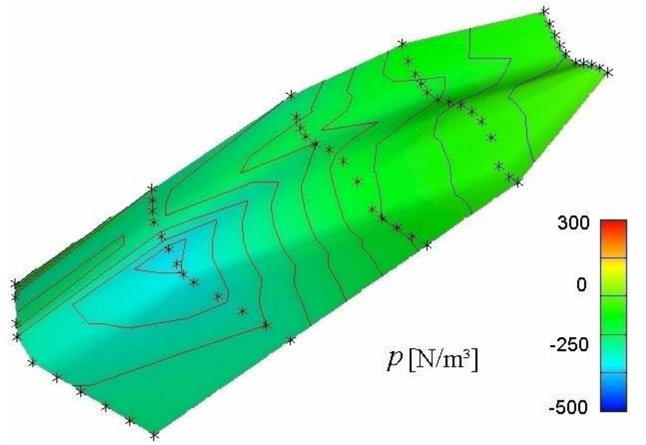


Figure 8: Pressure taps are indicated by asterisks

Pressure taps could be useful because they provide a quantitative output that can be used to authenticate numerical simulations. Another advantage of this method is that it has already been used at NSWCCD. The disadvantage is that pressure taps are extremely tedious and labor intensive to apply. Since pressure taps are located at discrete points on the hull, they need to be installed at every possible location at which a reading is desired. This technique also requires extensive modification of the model hardware, and in addition, many wires from the sensors. The sensors and data handling hardware and software are also highly expensive.

Pressure Sensitive Coating

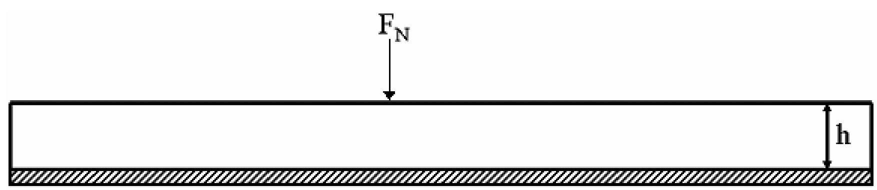


Figure 9: The thickness h of the pressure sensitive coating is a function of the normal force F_N

The second method for determining pressures is the use of a pressure sensitive coating. Much like the skin friction sensors discussed above, the pressure sensitive coating is another film currently in development by ISSI. The coating is an elastic polymer lightly doped with a fluorescent dye. When a normal load is applied to the film, the film deforms elastically but does not permanently compress or yield, therefore real-time photos are needed to document the film sensitivity relative to pressure. The thickness of the film is a function of the applied force, the initial thickness, and the shear modulus of the film. The fluorescence of the coating is a linear function of pressure, so pressure differences can be measured from the relative intensities of the film at flow on and flow off conditions (Figure 10). The film properties can be modified for different pressure sensitivities.

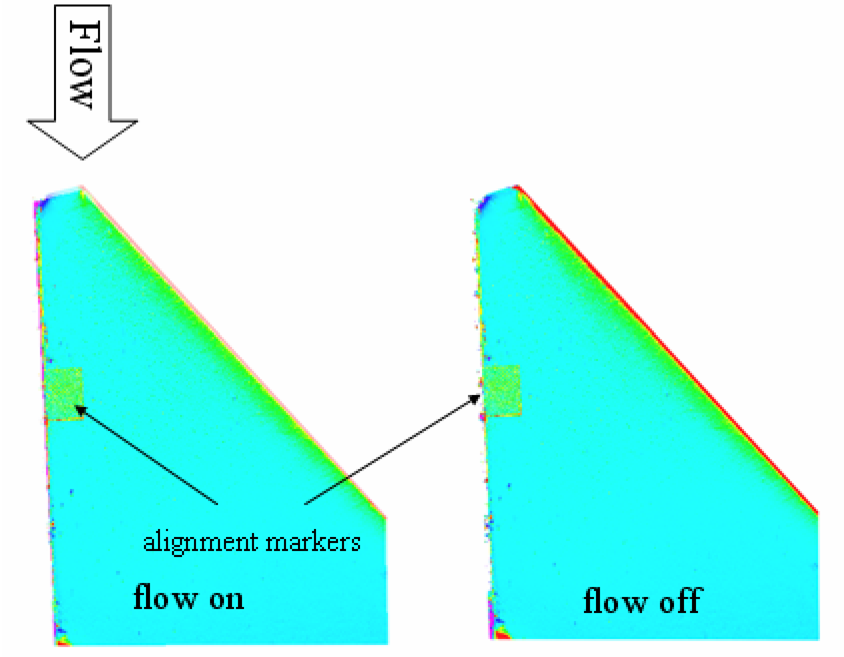


Figure 10: Pressure sensitive coating output at the flow on and flow off conditions and their relative fluorescence intensities

ISSI reports that this coating provides superior results to other pressure-reading techniques for flow on hulls. As opposed to the pressure taps providing discrete pressure readings, this particular coating allows continuous pressure readings. The process is also far less tedious and labor intensive.

As this product is still in development, the integrity of the results and the cost are both uncertain. The only reported results have been through ISSI, the company developing the technique; therefore, the actual quality of the results is uncertain. Cost information is also not yet available.

Wakes Between the Hulls

The third area of interest for visualizing flow is wakes between the hulls. Since a trimaran hull configuration has three hulls, it is crucial to know how the wakes created by the hulls interact with each other. This would greatly improve the ability to design multihulls.

Particulates

In order to visualize the wakes created by the hulls, the particulate method, floating particulates dispersed into the water, is available. The particulates conform to the motion of the wakes to follow the wake interactions, and Particle Image Velocimetry (PIV), which is discussed in depth later in the report, is employed to provide measurements and descriptions of the motion.

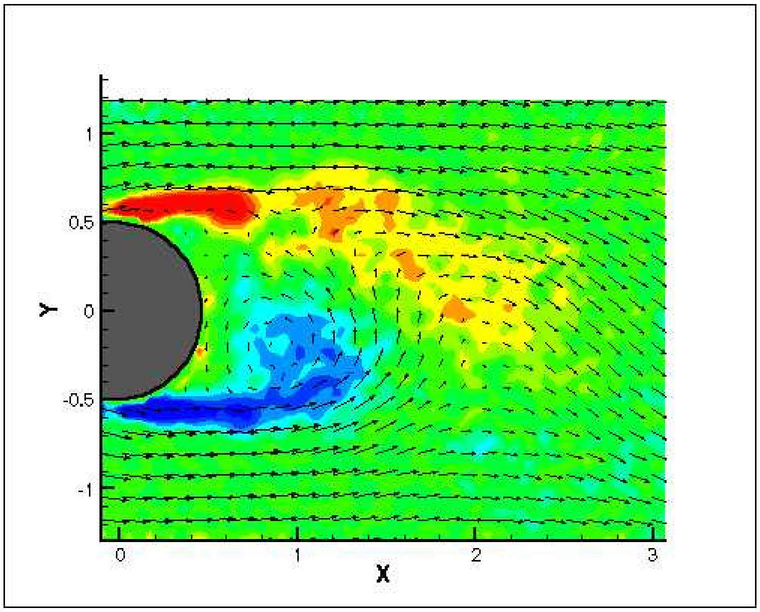


Figure 11: Velocity field around a bulbous bow

A quantitative output is produced when using PIV but a qualitative picture can also be obtained (see Figure 11). The method is already used at NSWCCD; therefore, the cost to develop the system and purchase equipment has already been spent. The drawback is that the dispersal of particulates into the water introduces a foreign substance that could pollute, disturb, and even alter the natural wake occurrences.

Flow Around the Hulls

The ability to examine flow behavior in the vicinity of the hull introduces valuable new perspectives for improving design. In order to visualize flow around the hulls, multiple techniques can be applied. Each technique involves the addition of extra substances, solid or liquid, into the water surrounding the hull, and real-time photography.

Dyes

When using dyes for flow visualization, an extra liquid substance is injected through a manifold into the water in order to track flow optically. The dye can be food coloring, fluorescent dye, or even soy sauce, as shown in Figure 12.

Figure 12: Turbulent transition in array of mm scale jets, visualized with soy sauce at University of Colorado

The use of dyes for flow visualization is beneficial because the materials are inexpensive and the process is relatively simple. The technique produces immediately visible results as well. However, dyes only provide a qualitative reading of flow. Furthermore, the use of dyes involves the addition of a foreign substance into the water, which pollutes the water and can interfere with flow. The manifold needed to inject the dye costs extra and can disrupt the flow as well. Another property of dyes that inhibits its ability to track flow is that it disperses very soon after injected.

Particulates

When using particulates for flow visualization, additional visible solid substances are dispersed into the water, typically through a manifold in a seeding process to provide adequate mixing. Finally, real time pictures are taken to track the movement of the particles.

Figure 13: Rheoscopic Fluid

Some particulates are inexpensive and easy to purchase. Using particulates to track flow does not pollute the water as much as dyes since the solid particles can settle at the bottom of a test tank. Moreover, quantitative results are possible, along with qualitative results, which allows for an expanded range of data.

The addition of a foreign substance into the water does pollute it somewhat and can sometimes disrupt the flow. The particulates need an extra seeding mechanism, which presents an additional cost. This seeding mechanism can also interfere with the flow around the hulls. Furthermore, particulates tend to have a positive and negative buoyancy range, which means that they might not strictly follow the flow of the water.

Streamers

This method involves strings attached to a manifold, which are then submersed into the water. The manifold, attached to the carriage in front of the model, is pulled through the water at a certain speed. The movement of the streamers traces the water flow around the hull. At the same time, photographs are taken to document the streamer positions and the flow interaction. The pictures can later be enhanced on image editing software (Figure 14) to make the strings more visible.

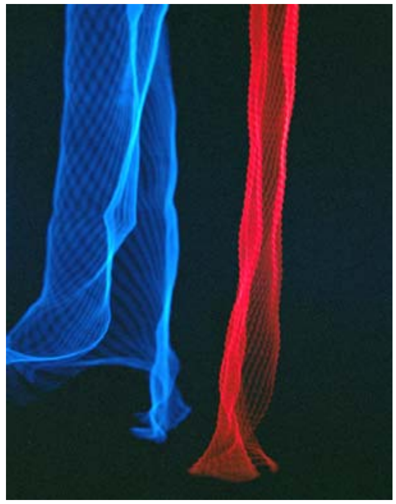


Figure 14: Digitally enhanced streamer photograph

This technique is inexpensive and requires basic materials. It also does not pollute the water since the streamers are attached to a manifold and not allowed to freely disperse. However, while the materials of this method are basic and inexpensive, the tow tank time needed to run several trials could increase the costs. Also, the manifold to which the strings are attached presents an extra cost and could potentially interfere with the flow. The quality and integrity of the data is also questionable. The long, flowing nature of streamers can be beneficial to visualizing fluid dynamics; however, these characteristics also mean that the streamers are prone to tangling.

Molecular Tagging Velocimetry and Thermometry (MTV&T)

MTV&T is a technique in which simultaneous velocity and temperature measurements can be obtained. This method involves the seeding the water with phosphorescent molecules which glow upon excitation by photons of the appropriate wavelength. A pulsed laser is used to “tag” the tracer molecules. Images are then taken at two successive times within the photoluminescence lifetime of the tracer molecules, which provide the estimate of the fluid velocity vector. The simultaneous temperature measurement is achieved by taking advantage of the temperature dependence of the phosphorescence lifetime, which is estimated from the intensity ratio of the tagged molecules in the two images.

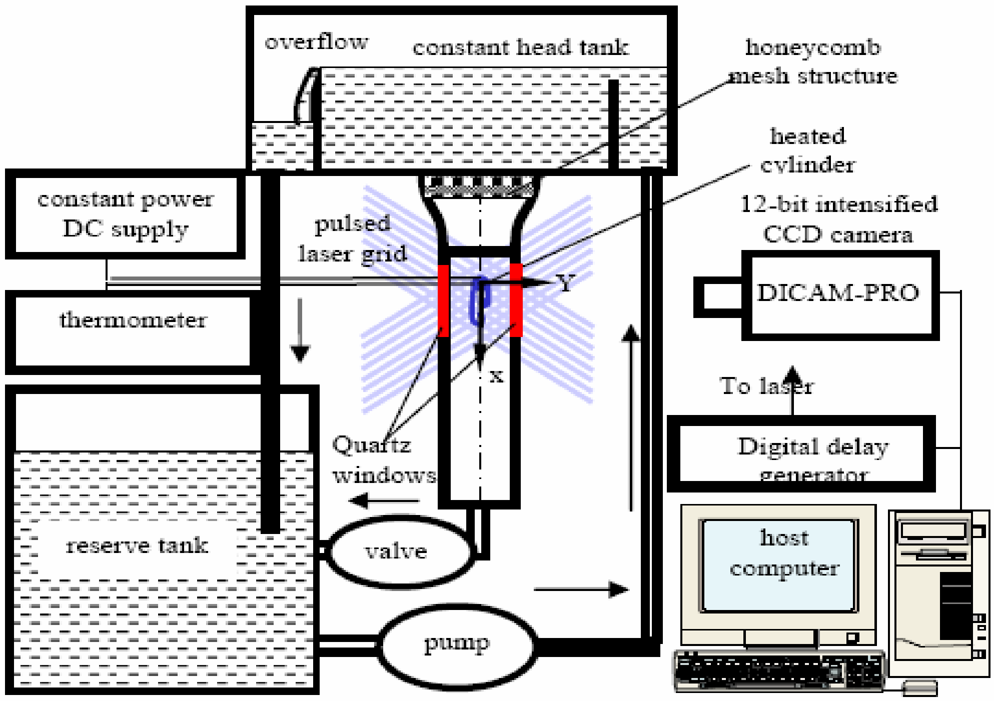
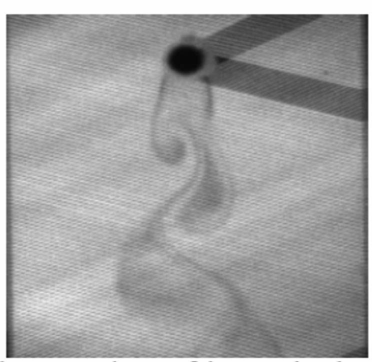
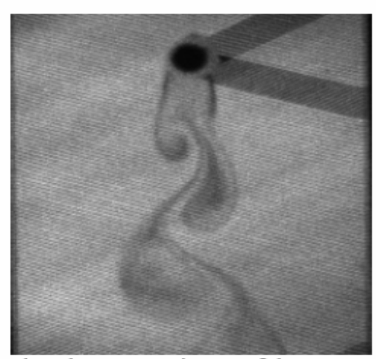


Figure 15: MTV&T Experimental Setup

The experimental setup is shown in Figure 15. Water is pumped from a reserve tank into a constant head tank, which is used to maintain a steady in-flow into the main water channel. As the phosphorescent molecules are seeded into the main water channel, a laser pulses in a grid and "tags" the molecules. A valve is located at the end of the water channel to adjust the velocity of the water. A power source, thermometer, computer, and camera are all attached to the system in order to record the data.

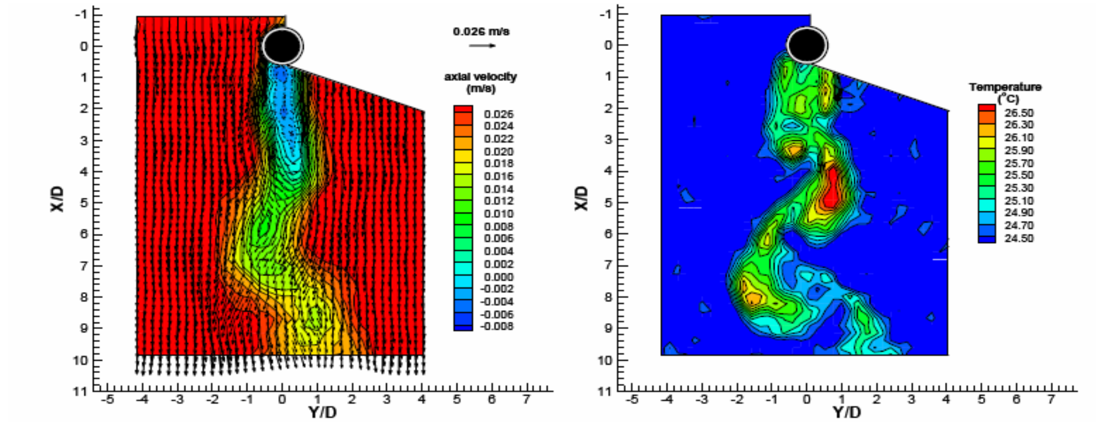


(a). phosphorescence image of the tagged molecules acquired at 1.0 ms after the laser pulse



(b). phosphorescence image of the same tagged molecules acquired 5ms later

Figure 16: MTV&T raw experimental data



(c). instantaneous velocity field derived from the image pair. (d). the derived simultaneous temperature field.

Figure 17: Derived velocity and temperature fields

As can be seen from Figures 16-17, simultaneous velocity and temperature data are obtained providing both quantitative and qualitative representations. The drawbacks are that this method is high in cost and requires sophisticated equipment. Since this method has not been performed at NSWCCD, it would cost extra to develop a system to perform the MTV&T technique in one or more of the testing basins. The method also involves the introduction of a foreign substance, which may pollute the water and be difficult to clean.

Particle Image Velocimetry (PIV)

The final flow visualization method discussed in this report is Particle Image Velocimetry, a particulate and optical method used to measure velocities in fluids. It has seen some use for 15 to 20 years but is still generally considered to be state of the art. The PIV system at NSWCCD was custom developed and has been in use since 2003. It was used recently for towed array tests. Previously, it had been used for roll tests and submarine turning tests.

The NSWCCD PIV system uses a rhodamine organic dye laser powered by flash lamps. The energy level is one joule per laser pulse. The laser unit is contained within a cabinet that can be located on one of the moving carriages or in the photo pit on the north side of the high-speed basin. The output is directed through a flexible optical cable inside a protective plastic sheath. The optical cable then terminates in a sealed optics unit that is mounted underwater. The optics unit contains a number of lenses with a rounded one at the end that spreads the laser light into a sheet. The laser light sheet is planar in nature but also has a thickness of about a half-inch. It is, therefore, three-dimensional and provides illumination in the water during the individual laser flashes. Images are collected with two cameras that are also mounted underwater. They are angled appropriately to capture the visual data. Cables from the camera units are contained inside plastic tubing and are strung back to computers for data collection. Like the laser unit, the computers are located in cabinets either on the carriage or in the photo pit. They run the Windows operating system and also have software that specifically works with the visual images from the cameras. The software is able to track individual particles in the water at two successive times and calculate velocity vectors with magnitude and direction.

The particles that are used are neutrally buoyant glass micro spheres. There is some variation among the particle densities. Some will tend to settle to the bottom of the tank while others will tend to float. Overall, however, the particles are small and follow the movement of the water. They are introduced through a manifold into the region around the model being tested. The manifold can be operated by hand, mounted in the tow tank, or mounted on the carriage and run through the water. Particles in the water then form a cloud in the vicinity of the model.

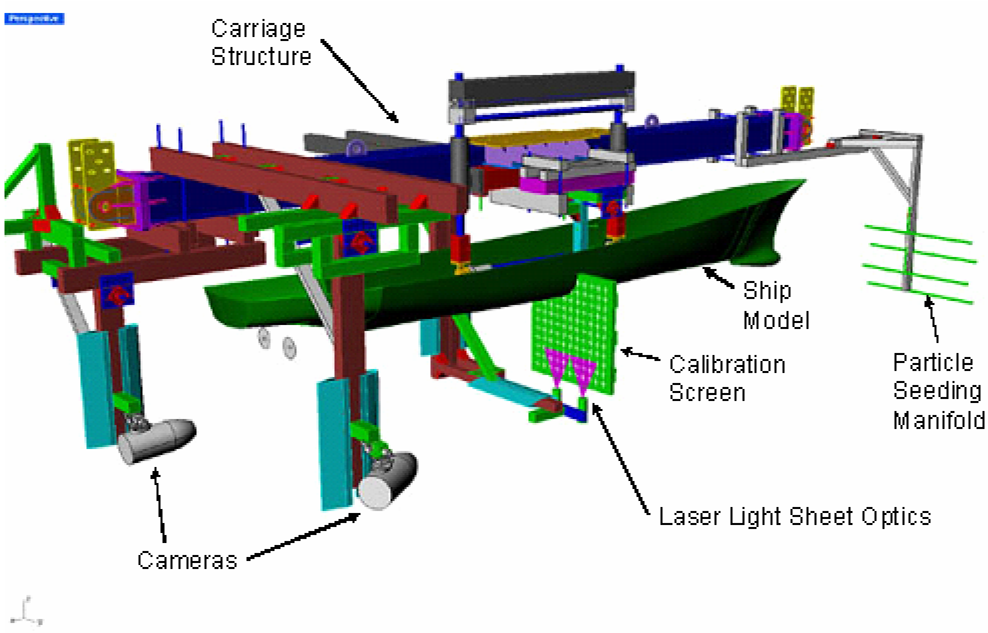


Figure 18: PIV Test Configuration

Pictorial representations of test setups are shown in Figures 18 and 19. The various components are easily seen. The carriage structure is above. The ship model is just below it. The laser light sheet optics and cameras are below or adjacent to the model. The particle-seeding manifold is on the right in Figure 18.

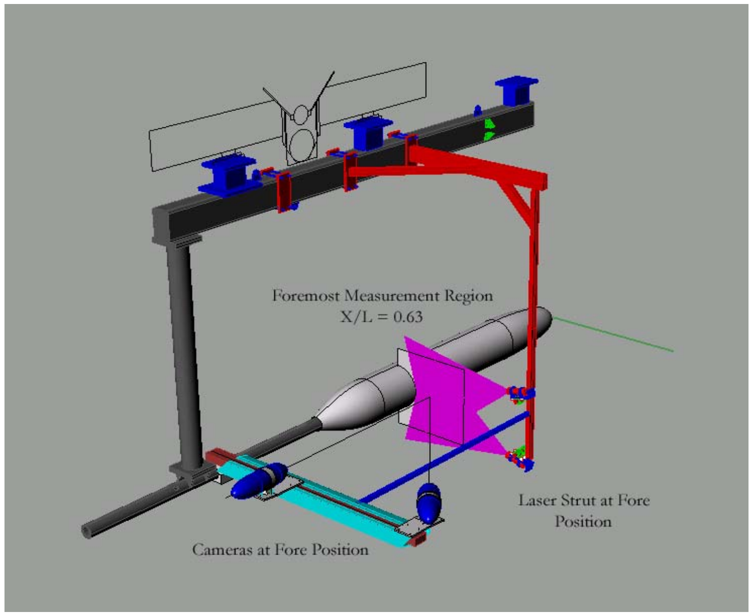


Figure 19: Closer look at camera and laser positioning in PIV setup

The laser light sheet optics, cameras, and particle seeding manifold are mounted on trusses and adjusted manually as needed for good results. The trusses must withstand the motion through the water in the tow tank. The calibration screen is used during the initial setup to ensure quality data collection from the cameras. The screen is cranked back up out of the water prior to the actual tests.

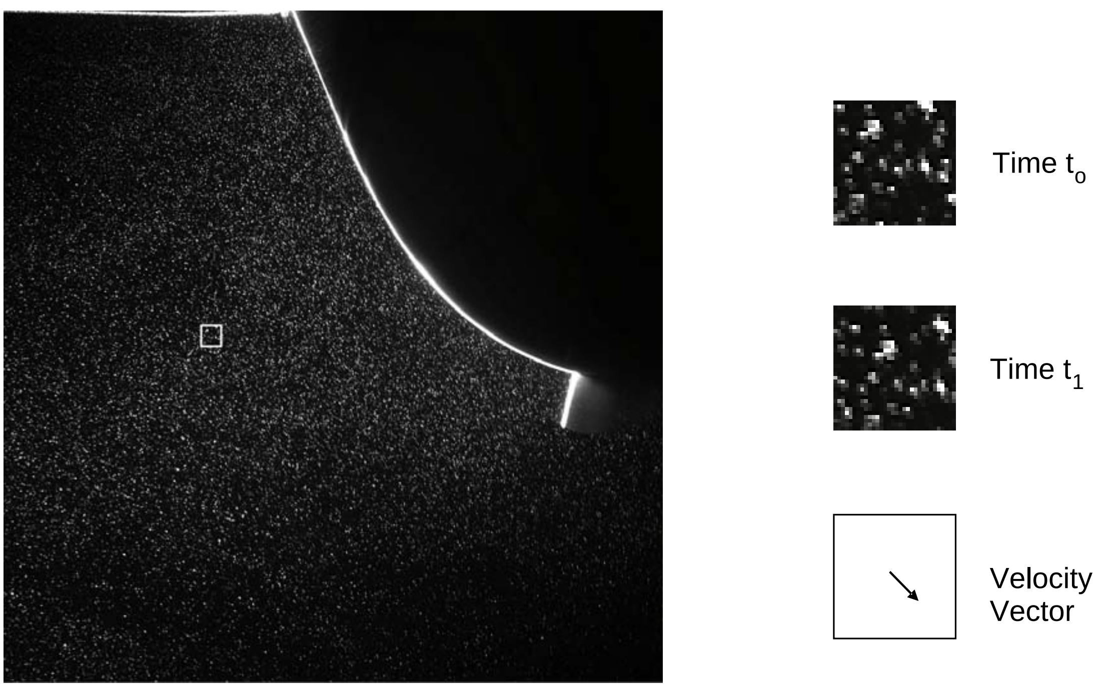


Figure 20: PIV raw test data

Raw PIV test data is shown in Figure 20. This particular example is from a roll test. The picture is a cross section perpendicular to the direction of motion. The dark area on the upper right is the model hull. The bright object on the middle right is a bilge keel. The cloud of particles can be seen as white dots. The pictures on the right show the acquisition of particle position data at two successive times, t_0 and t_1. The software then provides the velocity vectors.

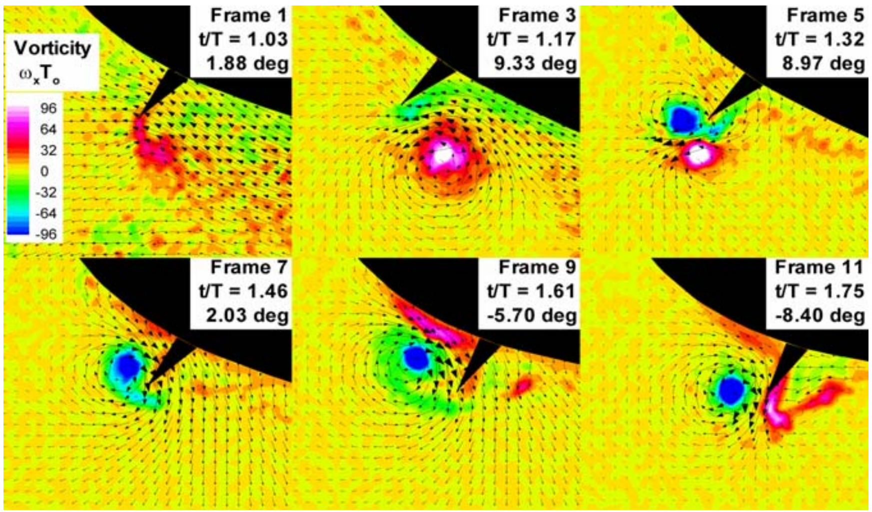


Figure 21: Sample PIV output from roll test

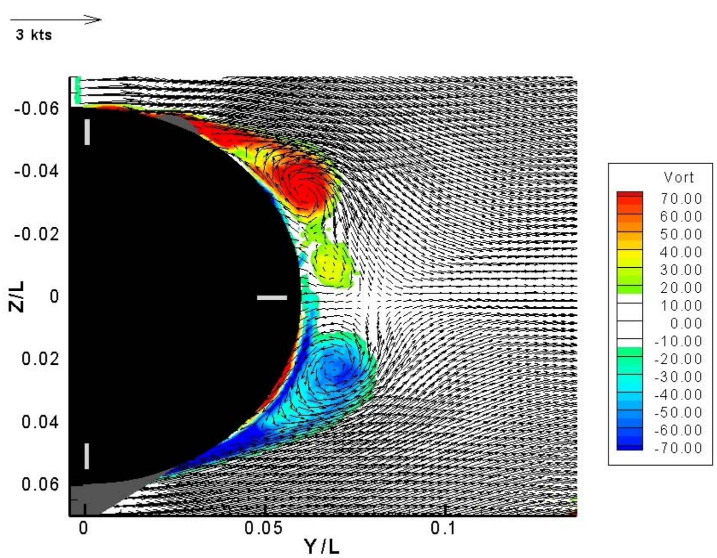


Figure 22: Sample PIV output

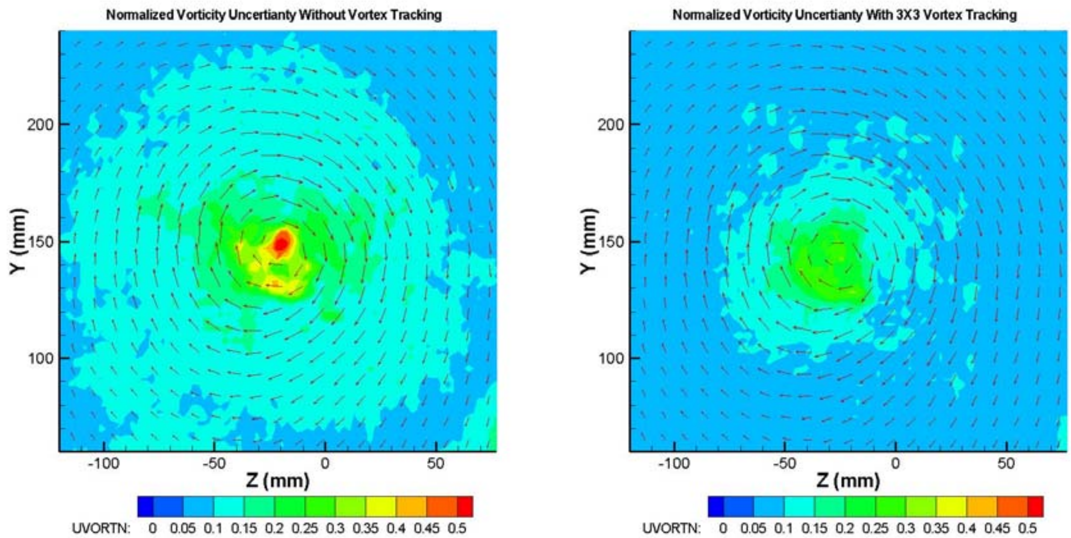


Figure 23: Normalized Vorticity Uncertainty Without and With Vortex Tracking

Sample processed PIV output is shown in Figures 21, 22, and 23. The arrows in the diagrams represent the velocity vectors in the fluid. All of the images show a two-dimensional output. The color-coding in these cases is used to represent vorticity. The output could be configured to let the color coding represent the third component of velocity instead. A three dimensional depiction of velocity may be necessary to compare with CFD output. The form of the output from any specific CFD code would have to be reviewed.

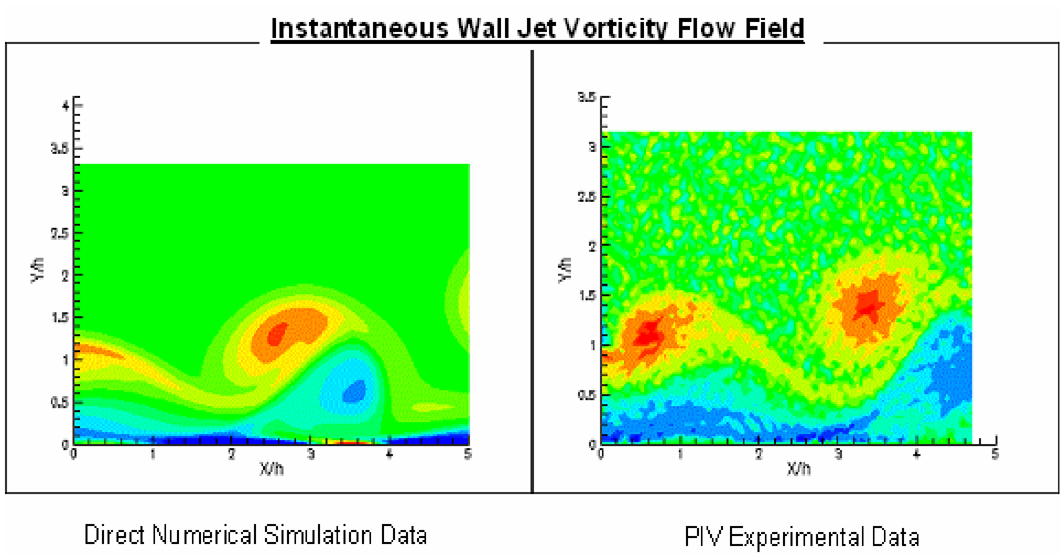


Figure 24: A sample comparison between direct numerical simulation data and PIV experimental data done by Florida State University

A direct comparison is easier to make when the data outputs are configured the same way for both cases. The example in Figure 24 can be animated to show the actual flow case.

The agreement between the computer simulated flow and the experimental data is then seen easily.
PIV is an in-house capability at NSWCCD already. It provides a qualitative and quantitative output that can be used to compare to CFD predictions. PIV measures an entire cross section of the fluid flow simultaneously and employs high-speed data processing. PIV has a wide spread history of use but is still considered a state of the art technique.

PIV is a high tech process. While not necessarily a disadvantage, it does require a certain skill level to work with it successfully. It is also labor intensive to set up the equipment initially and to make changes in the configuration for multiple test runs. Trusses and braces have to be set up to mount the laser light sheet optics and cameras. Moving the equipment for additional views might then require moving the truss supports. In some cases, however, it might be possible to mount the equipment in a stationary fashion off of a scissor jack at the bottom of the tow basin and then run the model past it.

The laser optics unit may sometimes need to be opened up for manual adjustment and alignment of the individual lenses. The camera units need purging with nitrogen to ensure clear pictures. Calibration of the cameras with the calibration screen is also needed prior to the test runs. The data acquisition software must be configured and the output checked beforehand.

Seeding the water with the glass particles must also be done beforehand. For the most part, they have neutral buoyancy. Still, some will slowly rise or sink and the water may need to be stirred occasionally to ensure an adequate particulate distribution. These particles are an added foreign substance in the tow tank and may need to be removed periodically. This could involve skimming from the surface or vacuuming off the bottom.

The trusses and braces, as well as the seeding manifold, may interfere with the fluid motion. Additionally, they may need to be repositioned repeatedly to try to obtain good optical viewing around trimaran hull configurations with bulbous bow sections.
The output of PIV is detailed and has high quality, but extra attention may be needed to display all three components of the fluid velocity vectors. PIV can be expensive, especially with a customized configuration, but the expense is a sunk cost at NSWCCD. It would be worthwhile to utilize this in-house capability so as to make full use of the investment already spent.

Recommendations and Conclusions

Flow visualization in each of the four areas requires different methods to achieve the best results. For visualizing the flow on the hulls, the artists' paint and linseed oil mixture seems to be the best. When measuring pressures on the hulls, further research should be done on the pressure sensitive film made by Innovative Scientific Solutions, Inc. (ISSI) to determine its usefulness for tow tank tests. It may also have some application for visualizing flow on hull sections. In order to visualize wakes between the hulls, PIV

should be used. Finally, when analyzing the flow around the hulls, PIV is the best technique.

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